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Neutralizing global warming impacts of crop production using biochar from side flows and buffer zones: A case study of oat production in the boreal climate zone

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ABSTRACT

Rapid climate change mitigation requires carbon sequestration in addition to greenhouse gas emission reductions. Agriculture may have a high potential for carbon sequestration due to improved practices. However, it is not known how the global warming impacts of crop production could be mitigated especially within an agricultural system. The aim of this study is to evaluate possibilities to neutralize global warming impacts in crop production using biochar produced from side flows and buffer zone biomass. A life cycle assessment methodology is utilized in this research for oat production in the boreal climate zone. Global warming impact reductions are compared for three different side flow utilization options. Traditionally, side flows have been utilized in energy or fodder production, and these options are compared to biochar production at a system level. The potential to use buffer zone biomass for biochar production is also studied. Willow has been selected as a biomass source in buffer zones. Oat production leads to greenhouse gas emissions especially due to the use of fossil and mineral fertilizers in cultivation and heat energy, electricity and fuels in various process phases. The production of one metric ton of oat flakes from cradle to gate generates 700 kg of CO_2eq emissions. Biochar and energy production from side flows enables a greater reduction in global warming impacts than the feed use of side flows. Buffer zones in willow biomass and biochar production may enable the full neutralization of the global warming potential of oat production within an agricultural system. Further research with actual measurements is required especially on biochar impacts on soil emissions such as N_2O. This research shows that it could be possible to neutralize global warming impacts from crop production using available technologies and available biomass in agricultural systems. A framework is created for carbon neutral crop production using side flows and buffer zone biomass through biochar.

1. Introduction

The growing global population requires increasing amounts of food. Agriculture is already responsible for 13% of global greenhouse gas emissions, and it is challenging to reduce the global warming potential (GWP) impacts of the agricultural sector (World resource institute, 2014). Agricultural processes and especially nitrogen fertilizer production consume high amounts of energy leading to additional indirect greenhouse gas emissions from energy production. Direct greenhouse gas emissions from agriculture are, for example, N_2O emissions from soils. The agricultural sector plays an important role in carbon cycles. Due to land use change from natural landscapes to agricultural landscapes, the carbon stock may also change, thus leading to GWP impacts. Agricultural practices play an important role in GWP impacts of farming, but these impacts cannot be fully neutralized (Moudry et al., 2018). However, agricultural processes may also increase soil organic carbon (SOC) and enable new carbon sinks. SOC has become an increasingly important topic in climate change discussions, and approximately 40% of the Earth's surface area is already harnessed for food production (Foley et al., 2011).

In simulations by Ouyang et al. (2013), adding SOC on agricultural lands plays an important role in reducing GWP impacts. Returning side flows from agricultural processes to soils is one of the ways to increase SOC content (Ouyang et al., 2013). Mosier et al. (2003) have calculated that it is possible to produce carbon neutral

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crops by increasing SOC. In carbon neutral crop production, a SOC increase mitigates emissions from other life cycle stages. One option to add SOC content is to use biomass for biochar production (Bartocci et al., 2016). Biochar can provide long-term soil carbon storage (Jha et al., 2010) to mitigate GWP impacts (Lehmann, 2007). Galinato et al. (2011) have observed that adding biochar to agricultural soil is a feasible method for carbon sequestration.

Various studies show a significant potential and possibility for biochar production using crop residues, such as the research by Clare et al. (2015) on straw in China, Thakkar et al. (2016) on agricultural residues, and Sigurjonsson et al. (2015) on straw in Denmark. Another option could be to use buffer zones for biomass and further on for biochar production. To prevent excess nutrient runoff into water systems, buffer zones are mandatory around fields. Buffer zones have been seen as a potential land area for energy biomass production in the Netherlands (Meeusen et al., 2000) and in Denmark (Christen and Dalgaard, 2013). Vassura et al. (2017) have demonstrated that it is possible to use buffer zone biomass for biochar production.

Crop cultivation in the boreal climate zone has been considered less efficient than cultivation in warmer climate zones because crop yields per hectare are usually lower. However, problems related to water use in irrigation, salination problems, pests, a lack of additional land area, etc., have led to a growing interest in food production also in cooler climate zones. Oat (*Avena sativa*) is the fifth most cultivated crop globally and can be used as human nutrition even though the majority of produced oat is directed to livestock fodder production (Statista, 2017). Oat has traditionally been produced mainly in cooler climate conditions than other popular crops. Global oat production covers approximately 10 million hectares and yields 23 million tons, and the majority of the production takes place in Northern Europe, Russia and Canada (United States Department of Agriculture, 2017). Globally, interest towards the use of oat as food has increased in recent years, and the oat trade volume has been growing (Agriculture and Horticulture Development Board, 2016) especially due to health effects such as cholesterol-lowering impacts (Othman et al., 2011).

There are a few previous studies on the carbon footprint of oat production. According to the studies, oat production leads to greenhouse gas emissions especially from agricultural processes. According to Katajajuuri et al. (2003), the carbon dioxide emissions are 370 kg $t^{-1}{}_{oat}$ and the majority of the emissions are related to agricultural practices such as fertilizers, agricultural machinery and drying. Finér (2009) has presented much higher emissions for oat production. Based on his research, producing 1000 kg oat generates 600 $kgCO_2eq$ from the cultivation process. Soil N_2O emissions have the highest climate impacts.

Oat production leads to various side flows such as straw, small oat and husks. The basic assumption by Katajajuuri et al. (2003) is that side flows from oat production are used in fodder production. Cherubini and Ugliati (2010) present that crop side flow use in bioenergy production has higher potential to reduce greenhouse gas emissions at a system level. Field et al. (2012) have compared biochar use in energy production and as a carbon storage in soils. According to their study, the use as a carbon storage reduces greenhouse gas at a system level more than use in energy production even if fossil energy production is substituted. A similar conclusion was drawn by Dutta and Raghavan (2014). According to Roberts et al. (2010), depending on land use change impacts, switchgrass production and use in biochar production can be a carbon sink if biochar is stored in soils.

Based on previous research, it is clear that by increasing SOC using biochar, the GWP impacts of crop production can be neutralized. It is also known that biochar can be produced from crop production side flows and from buffer zone biomass. However, it is not clear whether it is possible to produce enough biochar within a crop production system from sideflows and biomass from buffer zones to fully mitigate the GWP impacts of crop production. In addition, it is not clear whether side flow use for biochar production is the best option from the GWP perspective compared to energy and fodder use. By using biomass from buffer zones, land use for additional biomass production elsewhere can be avoided. This paper aims for the following objectives:

- To calculate the global warming impacts of crop production using oat as an example crop.
- To compare side flow utilization options from the global warming mitigation perspective at a system level.
- To assess the potential to produce biochar from buffer zones to further mitigate global warming impacts.
- To create a framework for carbon neutral crop production.

2. Materials and methods

2.1. Methodology and calculation models

A life cycle assessment methodology has been used to evaluate the GWP impacts of oat production in the boreal climate zone. The main protocols followed in this study are the ISO 14040, ISO 14044 and ISO 14067 standards. Characterization factors from Assessment Report 5 (AR5) of the International Panel on Climate Change (IPCC) have been utilized to ease the comparison to earlier GWP studies. This research is limited to a cradle-to-gate study. Fig. 1 presents the system boundaries of this study. The LCA model is created using a framework for agricultural LCAs presented by Brentrup et al. (2004). The life cycle assessment model has been modelled using the GaBi 6.0 software. The functional unit of the research is 1 t of oat flakes.

To evaluate the possibility to lower greenhouse gas emissions with different side flow utilization options, a system expansion approach has been used as presented in ISO/TR 14049. Thus also allocation processes can be avoided as recommended by ISO 14040 and ISO 14044. According to Cherubini and Ugliati (2010), side flow use may lead to unexpected land use change impacts. This can happen especially if in a basic case straw is ploughed into soil to increase soil quality and crop productivity. Straw use in other systems may decrease crop yields, which may lead to land use change

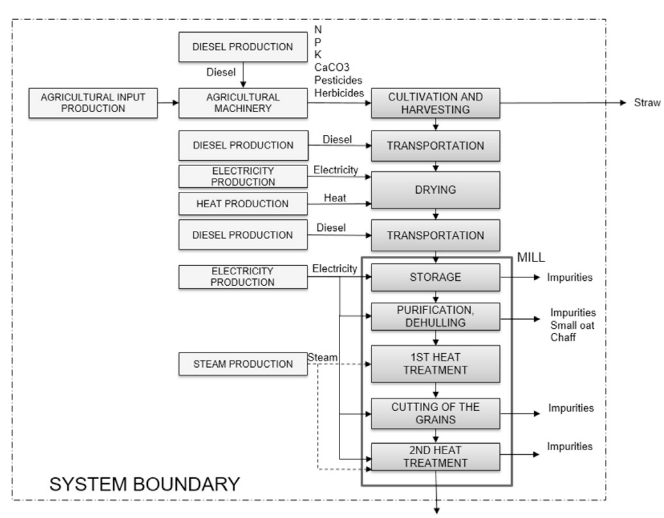

Fig. 1. System boundaries and life cycle process steps of the calculation model.

impacts. Consequently, only sideflows, such as small oat and husk, which are removed from fields are considered in this study. Side flows can be transported to a feed production site to be used as part of feed mix providing fibre for cattle. It is also possible to combust side flows in a boiler and produce steam either at a mill or in a larger district heating plant. There are multiple studies on agricultural side flow use for biochar production through pyrolysis e.g. by Park et al. (2014) on rice production straw and by Pfitzer et al. (2016) on wheat production side flows. Therefore, the third option for this study would be to employ pyrolysis to produce biochar and further on carbon stocks. The side flow utilization scenarios that are compared by using the system expansion method are:

- Scenario 1 (S1) Use as feed
- Scenario 2 (S2) Use as energy
- Scenario 3 (S3) Use as biochar

The system expansion approach assumes that if side flows are not directed to a feed factory, additional oat has to be used in feed production. If side flows are not used in energy production, natural gas has to be utilized to produce the required energy. Carbon in feedstock is eventually released into the atmosphere in S1 and S2, but in S3, it can be stored for a longer period as biochar. Fig. 2 presents the system expansion method and scenario comparison.

An additional evaluation has also been carried out related to the potential to use biomass from buffer zones for biochar production. This increases the potential for carbon sequestration within the agricultural system in addition to side flows.

2.2. Data and assumptions

An oat mill in Lahti, Finland, has been chosen as the case production plant for the calculation model. The mill produces 21 900 t of oat annually. Primary data on the mill operations have been gathered from the mill. Primary data on cultivation in different regions in Finland have been collected from national databases such as the Natural Resources Institute Finland (2014). Secondary data from literature and from the GaBi database have also been used to support the life cycle assessment. Gabi databases have mainly been used for energy production operations as well as for transportation and fertilizer production processes. The main GaBi databases used in modelling are GaBi professional and energy extension.

2.2.1. Oat cultivation and transportation

Cultivation processes require different agricultural machines. It is assumed that one drive per each crop is required for harvesting, seeding, ploughing and fertilizing. Spreading pesticides, herbicides etc. requires two drives. These processes are modelled based on the cultivation of 1 ha of oat and on agricultural machinery processes provided by GaBi 6.0 databases.

Oat is produced and imported to the mill from different regions in South-west Finland. Table 1 presents the amount of oat from each region and the average oat productivity in each of the regions using primary data (P). It also presents the rough amount of straw that is produced as side flow of crops using secondary data (S). Straw is currently mainly ploughed back into soil in Finnish fields. Table 2 presents the average fertilizer amounts used for oat cultivation. It is assumed that approximately 1% of nitrogen input on soil is released into the atmosphere as N_2O (Brandão et al., 2011).

The harvested crop is transported to a dryer where additional moisture is removed using heat, and thus the weight of the crop is also reduced for longer-distance transportation. The following energy consumptions are used for drying: 0.559 MJ kg_{oat}^{-1} heat, 0.036 MJ MJ kg_{oat}^{-1} electricity. Typically, heat is produced by fossil oil, but in some cases, also biomass heat is applied (Ahokas and Jokiniemi, 2014). Electricity is assumed to be taken from a local grid. Drying reduces the oat mass from 1.14 kg to 1.00 kg (Ahokas and Jokiniemi, 2014). The input humidity into a dryer is 25% and oat is dried to 14% humidity.

Transportation from the field to a dryer is assumed to be approximately 2 km and is carried out in a truck with a 7.5 t payload. Oat is transported from dryer to mill by trucks with a 42 t payload. Table A presents the average transportation distances from dryer to mill.

2.2.2. Oat mill operations

The mill operation data is collected from an oat mill in Lahti and is supported by data provided by Finér (2009).

The first processing phase of the mill is the preliminary cleaning of the grain intake. For the purpose of this study, it was assumed that 0.3% of the intaken mass is removed from the material flow, and the electricity consumption of the intake, preliminary cleaning and grain storage is 9.5 kW h/t grain (Finér, 2009).

The next phase in the mill is the grain purification, weighting and dehulling. The oat grains are cleaned and screened, and grains less than 2.0 mm in diameter – small oat – are separated from the material flow. For this study, it was assumed that 3% of the material flow is impurities and 6% small oat. After cleaning and sorting, the oat grains are dehulled. It is assumed that the mass of oat hulls is 27.5% of the cleaned and screened oat material flow. The electricity consumption of cleaning, screening and dehulling is assumed to be approximately 28 kW h/t grain (Finér, 2009).

The next process is the steam addition followed by the cutting of

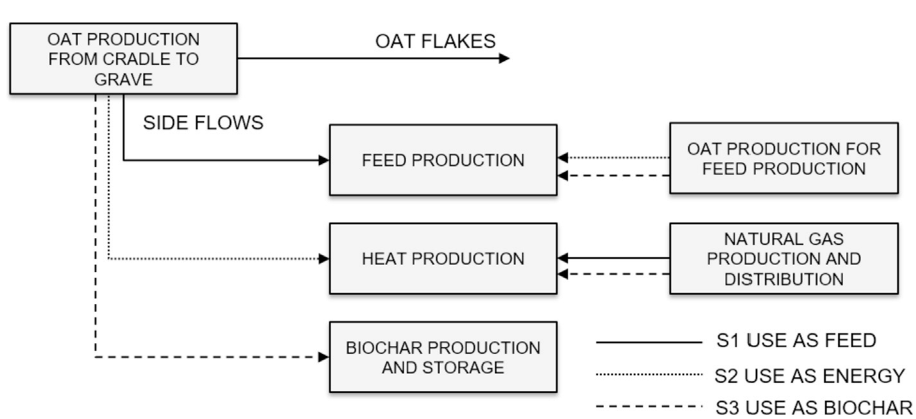

Fig. 2. System expansion method.

Table 1
Data for cultivation processes based on region.

Region	Häme	Satakunta	Southeast Finland	Southwest Finland	Pirkanmaa	Uusimaa	Data type (P/S)	Data Source
Oat production [t a^{-1}]	10 000	2000	2000	2000	2000	2000	P	Local oat mill
Oat productivity [kg ha^{-1}]	3780	3750	2930	4180	3170	3540	P	Natural Resources Institute Finland (2014)
Straw production [kg ha^{-1}]	3000	3000	3000	3000	3000	3000	S	Rasi et al. (2012)
Transportation distance to the Mill [km]	100[a]	490	224	430	256	210	P	measured by using a map

[a] 10% of oat in Häme is transported 50 km distances by tractor.

Table 2
Input data related to cultivation processes in Finland (Natural Resources Institute Finland, 2014; Elosato, 2015).

	Input as nutrient	Input as fertilizer	Fertilizer type
Nitrogen [kg ha^{-1}]	100	100	Nitrogen fertilizer
Phosphorus	10	16.7	Triple superphosphate
Potassium	12.5	20.8	Potassium chloride
Calcium	138	344	Limestone flour
Pesticides, herbicides, etc.	0.98	0.98	Pesticides

the grain. It is also that 1.5% of the oat grain intake is lost during the processing. After cutting comes the flaking process, which includes a second steam addition. It is assumed that the material loss in the flaking process is 1.5%. It is assumed that 5% of the grain mass delivered to the mill is lost due to a reduction in grain moisture content. This loss is taken into account before the packaging phase (Finér, 2009). The total steam consumption in these processes is 155 kW h/t grains and the total electricity consumption is 120 kW h/t grains.

The mill uses electricity from the Finnish national grid with the exception that 30% of the energy is assumed to be wind power. Grid electricity in Finland is roughly 34% nuclear, 24% hydro, 16% biomass, and 10% coal, and the rest is produced mainly with natural gas, wind and peat. The emission factor of grid electricity is approximately 340 gCO_{2eq}/kWh. In the base case, the heat and steam demand of the mill operations is covered by burning light fuel oil.

Chaff burning: For this study, it is assumed that the lower heat value (LHV) of oat chaff is 13.0 MJ/kg, the operating moisture content is 20% and the ash content per dry matter is 5%. Of all of the grain sorts, oat has the lowest heat value and its straw has a tendency to sinter. According to Alakangas et al. (2016), the efficiency of heat production is assumed to be 60%.

2.2.3. Biochar production

An option to reduce or eliminate the GWP of oat cultivation could be the production of biochar from biomass produced in buffer zones. We have randomly selected three different field areas in the case region to estimate the buffer zone capacity using maps provided by the National Land Survey of Finland (2017). Table 3 presents the data, based on which we have decided to choose a high buffer zone variation from 5 to 12%.

Willow has relatively high biomass productivity in Finland, from 6 to 9 t dry matter per hectare, and it has been selected as the example biomass for buffer zone biomass production (Lauhanen and Laurila, 2007). Biochar production from willow is explained by Saez de Bikuña et al. (2017), who also show that the carbon sequestration potential of willow biochar is much greater than the GWP impacts of willow and biochar production. The amount of biochar from biomass depends on the biochar technology and operating parameters such as temperature. Brassard et al. (2018B) conducted a pilot scale study for switchgrass and received a higher yield with lower temperatures. Similar conclusions have also been presented by Mašek et al. (2013B). The yields in their study ranged from 20% to 29%. According to Mašek et al. (2013B), at temperatures higher than 500 °C, the biochar yield was less than 30%. According to Hodgson et al. (2016), the amount of biochar was 26% of the willow dry weight. Much higher yields have also been presented. Mašek et al. (2013A) present a 27–90% yield of willow dry weight. Higher yields can be reached only at low pyrolysis temperatures. According to Jindo et al. (2014), the carbon content of biochar at high pyrolysis temperatures is over 80% for woody feedstock. Biochar stability in soils depends on the biochar's characteristics as well as on environmental factors. According to Enders et al. (2012), an O/C_{org} ratio below 0.2 or an H/C_{org} ratio below 0.4 have the highest potential for C sequestration. According to Brassard et al. (2018B), these ratios are can be achieved at higher pyrolysis temperatures. Due to uncertainties related to the biochar carbon yield from willow presented in the literature, we have decided to include a variation from 20 to 30% of willow dry weight in the calculations representing especially pyrolysis at higher temperatures. The last important factor related to biochar potential in GWP mitigation is biochar stability. Budai et al. (2013) have stated that 70% of the C in highly stable biochar could remain in soils after 100 years. However, also other assumptions have been made in previous studies ranging from 50% (Brassard et al., 2018B) to 90% (Peters et al., 2015). A variation from 50% to 90% has been used in this study.

Table 3
Three case fields and their buffer zones.

Field	Cultivation area [ha]	Buffer zone area [ha]	Share of buffer zone in total area [%]
Field 1 Maavehmaa	79	6	7
Field 2 Huhtaranta	24	3	10
Field 3 Arola	87	5	9

For oat production side flows, a similar approach has been taken to calculate the potential to produce biochar. There is no exact data on biochar production from oat production residues, and therefore, we are using values presented for straw in literature. Park et al. (2014) have investigated rice straw pyrolysis, and in their research, the yield varied from 20% to 30% at higher temperatures. Approximately similar results have also been presented by Pfitzer et al. (2016) for wheat straw. In this paper, we have used 25% (20–30%) as the yield for biochar carbon production from oat production side flows and 70% (50–90%) for biochar stability over 100 years. The values in parenthesis have been used in the sensitivity analysis.

3. Results

Fig. 3 presents the cradle to gate GWP impacts of Finnish oat production divided into main life cycle steps. As the figure shows, the majority of greenhouse gas emissions are caused by nitrogen fertilizer production and soil N_2O emissions from nitrogen fertilizer use. Nitrogen fertilizers are produced by natural gas steam reforming and the Haber-Bosch process, which consume large amounts of fossil natural gas. Other notable life cycle steps are the use of agricultural machinery, dryer steam production, mill electricity production and mill steam production. Agricultural machinery consumes fossil diesel, dryers consume fossil oil, and mill steam is produced from fossil natural gas. Mill electricity is a mix of different electricity production methods. It should be taken into consideration that side flow use is not included in Fig. 3.

Fig. 4 presents the comparison results of oat production side flow utilization modelled with the system expansion method. The figure separately presents fossil GHG emissions and biogenic GHG emissions from the side flow use. As the figure displays, the lowest total GHG emissions can be achieved if side flow carbon is used for energy production or for biochar production and stored into soils. The differences between options are relatively small and there is uncertainty especially related to biochar production potential.

Fig. 5 presents the sensitivity of the results by assuming 10% variation in different factors. For biochar production a maximum variation based on uncertainties in initial data is presented. For dryer and mill steam production, the assumption is made that steam is produced using biomass such as side flows from the oat production processes. As the figure shows, the highest uncertainty is caused by biochar production and the nitrogen fertilizer amount and production related emissions. If yields are higher than 25% and more than 70% of biochar is stabile after 100 years, biochar use seems to be the best option from the GWP perspective. Using biomass in steam production at a mill possesses more potential to reduce GWP compared to natural gas use. In this paper, we assumed that 1% of nitrogen reacts to N_2O. The results are also sensitive to this assumption, and more research is required related to N_2O rates from soils.

Fig. 6 presents stabile (over 100 years' time horizon) biochar production potential for willow in buffer zones. As the figure displays, biochar production varies approximately from 25 kg to

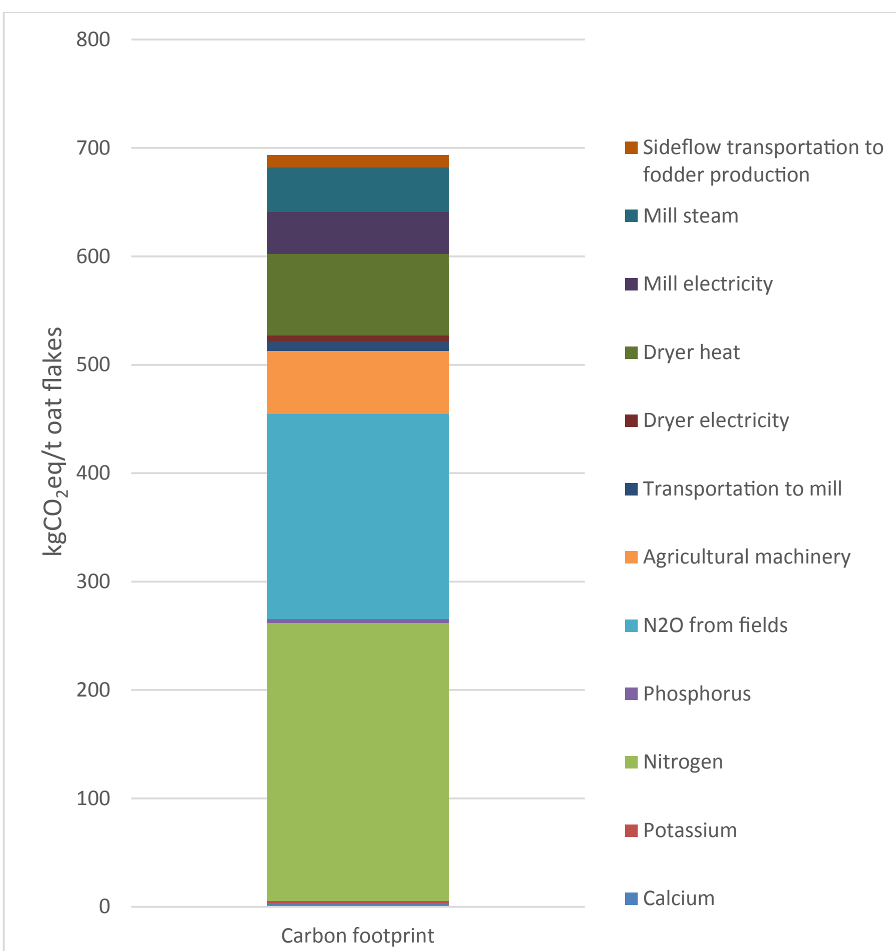

Fig. 3. Global warming potential from cradle to gate in oat production.

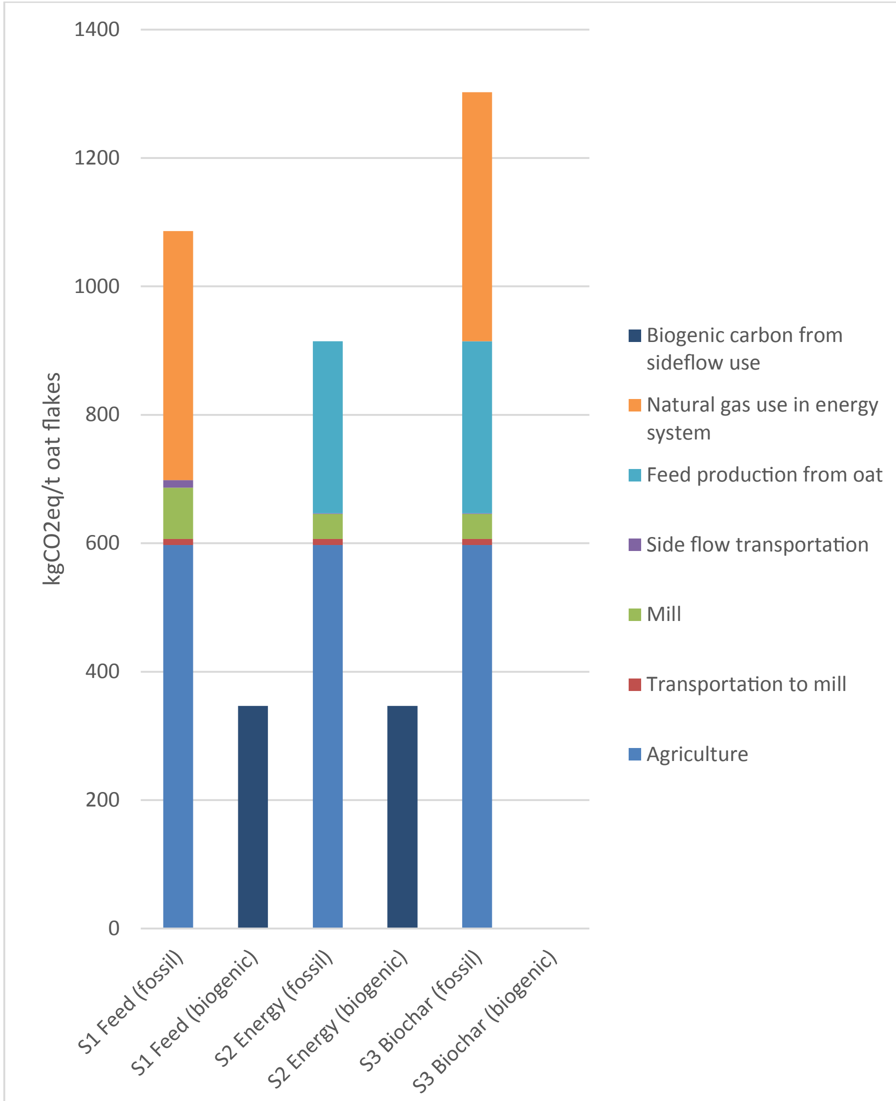

Fig. 4. Comparison of feed, energy and biochar use of oat production side flows.

200 kg per hectare. Fig. 7 presents the same results as sequestrated CO_2 for 1 t oat flakes. Fig. 7 indicates that the GWP mitigation potential varies from approximately 50 $kgCO_{2eq}$ to 390 $kgCO_{2eq}$. The variation of the results is especially due to willow productivity, buffer zone sizes, biochar productivity and stability over 100 years. In addition, uncertainty is also related to the carbon content of biochar, which was assumed to be 80%. The results suggest that the use of buffer zones to produce biomass for biochar feedstock and biochar storage in soils can eliminate a remarkable share of GHG emissions from the cultivation and processing of oat.

4. Discussion

Data on oat cultivation and oat mill operations was collected from primary sources, and therefore, it can be assumed that there are no major uncertainties. More uncertainties may be related secondary data especially on fertilizer production and N_2O emissions from soils. According to Cheng et al. (2014), major sources of greenhouse gas emissions in crop cultivation in China are nitrogen fertilizer production and N_2O emissions from nitrogen use. Similar results have also been presented for oat by Finér (2009). Our research confirmed these conclusions despite the fact that nitrogen fertilizer production led to slightly higher GWP than N_2O emissions. There is uncertainty related to the amount of nitrogen that reacts to N_2O. In our research, this amount was assumed to be 1%, and small changes to it can lead to relatively significant changes in N_2O GWP. There is also uncertainty related to emissions from nitrogen fertilizer production. GWP impacts from agricultural practices played the most important role in the total GWP impacts of oat production. These impacts were at the same level as presented earlier by Finér (2009).

Using biomass side flows from oat production provides a possibility to reduce GHG emissions related to oat production further. Biochar and energy production possess the highest potentials to reduce the greenhouse gas emissions of the system. Reductions in the energy case greatly depend on the replaced energy production method, which in this paper was assumed to be natural gas.

All of the major operational life cycle steps have been included within the system boundaries. Process steps such as the packaging and distribution of the final product were not included in the study but can be assumed to have a minor impact (Silvenius et al., 2011). The building of facilities was not included in the study but can be

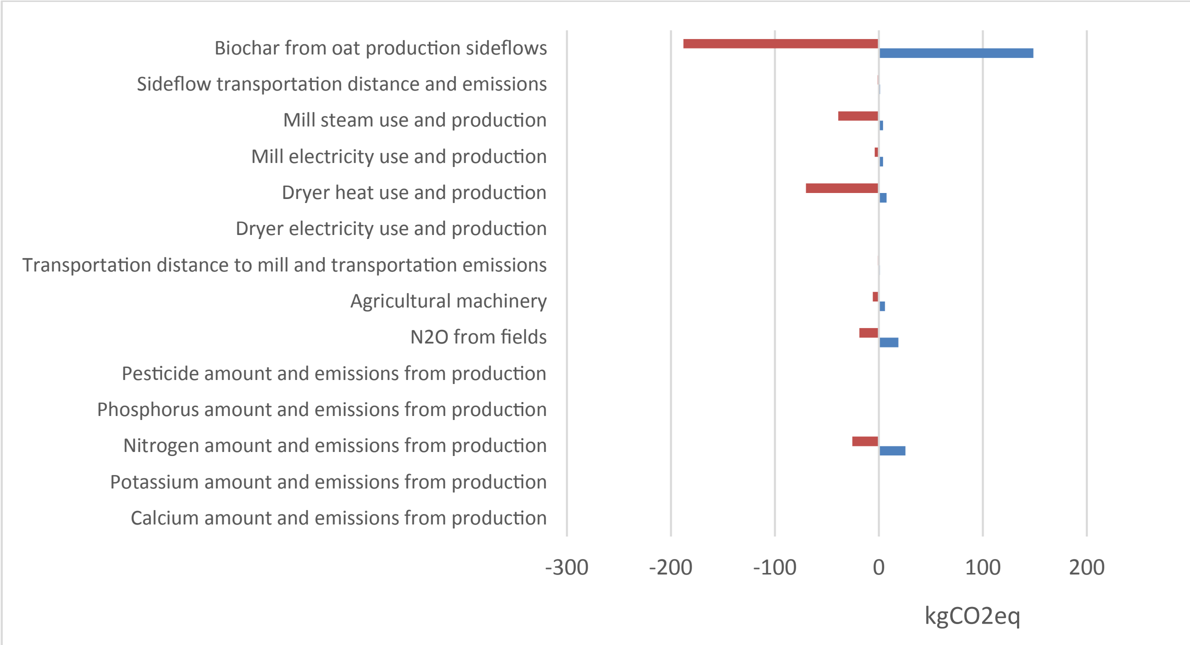

Fig. 5. Sensitivity of results.

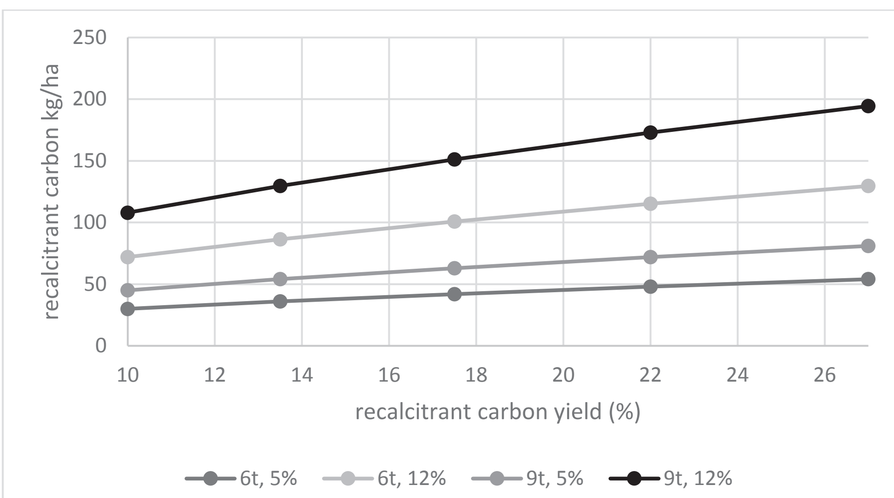

Fig. 6. Stabile biochar carbon productivity from willow cultivated in buffer zones. The willow productivity is calculated using 6 and 9 t/ha, and buffer zone sizes vary from 5% to 12% of the total agricultural land area.

assumed to have a minor impact on the results. The research concentrated only on GWP impacts, but future research should include also other sustainability aspects, such as particulate matter emissions.

The research was carried out in Finland. This affects especially energy production related emissions as well as average crops and willow productivity. An analysis in a warmer climate might have led to higher biomass and crop productivity. Electricity production related emission are relatively low in Finland.

Buffer zones play an important role in preventing excess nutrient offsets to water systems. They also enable maintaining rural biotopes that are highly endangered in Finland (Kontula and Raunio, 2013). According to Egbert and De Greve (2000), buffer zones can be crucial for both nature and people. Buffer zones could provide an opportunity to produce biomass that could be used to generate additional biochar. Depending on how the biomass is produced and how high a yield can be achieved in biochar production, this method could eliminate all GWP impacts of oat production. According to Peltola et al. (2010), timber production will increase significantly in Finland due to climate change. Similar development may also occur for crops and willow production in the future. This requires biochar storage e.g. in soils. The use of buffer zone biomass may also remove nutrients sequestrated into buffer zone vegetation and thus help to reduce nutrient runoff from buffer zones when they can no longer uptake nutrients effectively (Parkyn, 2004). Biochar in soils may also help to retain nutrients in agricultural soils, thus reducing runoffs and maintaining soil fertility (Barrow, 2012). Zhang et al. (2010) have conducted biochar research related to rice production, and based on their study, adding biochar into soils decreases the amounts of N_2O but

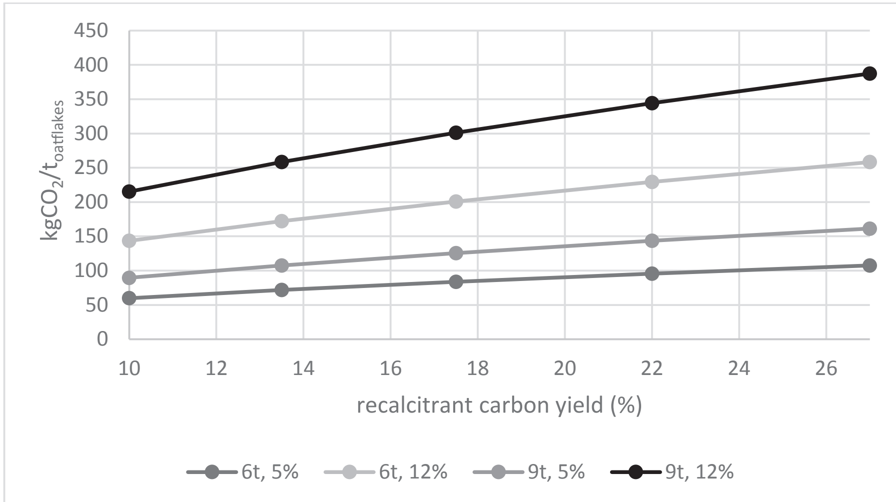

Fig. 7. CO_2 mitigation potential for willow cultivated in buffer zones. The willow productivity is calculated using 6 and 9 t/ha, and buffer zone sizes vary from 5% to 12% of the total agricultural land area.

increases the amount of CH_4. Brassard et al. (2018A) have concluded that biochar addition to soil could reduce soil N_2O emissions by 42–90%. Rittl et al. (2018) could not find significant changes in soil N_2O emissions due to biochar addition. Their study indicates that the main advantage of biochar addition from the GWP perspective is an increased soil carbon stock. These impacts should be studied also for crops. Biochar use in agriculture has been demonstrated to increase crop yields while reducing fertilizing requirements and nutrient runoff from fields (Zheng et al., 2010). According to Aller et al. (2018), biochar use in corn production reduces nitrogen leaching by 2.5–205.

The next steps would be

- to test biochar production from buffer zone biomass;
- to test crop productivity impacts by adding biochar into soils;
- to test soil biochar impacts on nutrient cycles.

According to Koppejan et al. (2012) and Shackley et al. (2011), biochar production costs from woody biomass vary approximately from 130 to 310 €/t. Clarke et al. (2014) have assessed that a carbon price below 100 €/t by 2030 should be sufficient to limit global warming to 2 °C.

Based on the results of this research, a concept for carbon neutral crop production using biochar was developed. Fig. 8 presents the framework. There may also be additional GWP impacts

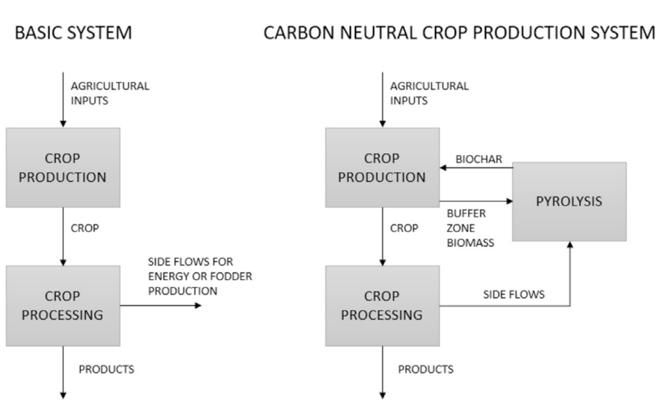

Fig. 8. Framework for carbon neutral crop production using biochar.

reducing possibilities for biochar addition if soil N_2O emissions can be reduced. In addition to creating a carbon sink, biochar contains phosphorous from feedstock. This may enable a reduction in phosphorous fertilizing, which should be further studied. Rehman et al. (2018) have stated that sewage sludge based biochar and its addition to soils for wheat cultivation seems to be a promising possibility for phosphorous fertilizing. The framework developed in this paper is applicable also to other crops than oat, but more numerical assessments should be done for different plants. The carbon neutral crop concept has been presented earlier by the Monsanto company, but the concept is not based on biochar or buffer zones but on improved agricultural practices, cover crops use and side flow returning to soils (Monsanto, 2017).

5. Conclusions

Oat production leads to GWP impacts especially due to fertilizer use in cultivation and energy use in different process phases. The total carbon footprint of oat production is approximately 700 $kgCO_2eq$/t oat. Various side flows from the process can be used as feedstock for feed, energy and biochar production processes. Biochar and energy production lead to the lowest total GWP impacts of the studied side flow utilization options at a system level. The differences were rather small, and more measured data on biochar production yields and stability for oat production side flows will be needed in the future. Biochar production from side flows could mitigate 350 $kgCO_{2eq}$/t oat.

Buffer zones could be used for biomass, such as willow production. This would enable additional biochar production and potential to sequestrate a maximum of 390 $kgCO_{2eq}$/t oat, which could in theory lead to carbon neutral oat production. This means that GWP impacts from crop production can be neutralized by producing biochar. Nevertheless, biochar yields greatly depend on the available buffer zones, willow biomass productivity and biochar yield from biomass. More research is also needed for additional advantages in mitigating GWP by biochar, such as the reduced need for fertilizing and lower N_2O emissions from soils. This is the first attempt to model how carbon neutral crop production could be achieved. Despite some limitations especially on biochar production parameters, a similar approach can be used to analyze carbon neutrality possibilities of other crops.

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